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Continuous unidirectional solidification of QAl9-4 Cu-Al alloy①

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Abstract: A continuous unidirectional solidification equipment with the advantages of electric-slag remelting, induction heating, continuous casting and unidirectional solidification was built to study the QAl9-4 Cu-Al alloy. The results show that the electro-slag induction continuous unidirectional solidification process can be used for the steady continuous unidirectional solidification of QAl9-4, and revitalizes the down-pulling continuous unidirectional solidification process; that the temperature distribution in the mold wall reflects that of the molten metal in the mold, thus the temperature distribution in the mold wall can be used to control the electric-slag induction continuous unidirectional solidification process; and that the mutual matching of the technological parameters is the key to stabilize the solidification process.

Key words: QAl9-4 Cu-Al alloy; continuous casting; electro-slag remelting; unidirectional solidification
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1 INTRODUCTION

The continuous unidirectional solidification technology, which is established by combining the unidirectional solidification with continuous casting, provides a new approach for the study of solidification theory and the development of new materials. Its emergence also marks the beginning of a new stage of the solidification technology. There appear two different continuous unidirectional solidification approaches supported by two different formation theories of equiaxed zones respectively[1,2]. One is the high temperature gradient approach proposed by Flemings *et al*[3], in which the depth of the molten metal is reduced to approach membrane so as to raise the temperature gradient in the melt before the solid-liquid interface, thus avoiding the formation of new nuclei. The other is OCC approach invented by Ohno[4], in which the temperature of the mold is heated to be slightly higher than the melting point of the cast metal to prevent the nucleation on the mold wall in the solidification process so as to avoid the formation of equiaxed grains, and make the melt solidify promptly as it is divorced from the outlet of the mold. Both the high temperature gradient approach and the OCC approach can realize continuous unidirectional solidification. Particularly, the OCC approach has been used to produce shaped materials with good surface brightness, complex cross-sections and unidirectionally solidified microstructures and without limit of length[5,6]. But for the solidification of ferrous metals and high melting-point nonferrous metals and alloys, both approaches leave room for improvement to some extent in melting, refining, heat preservation and continuous supply of melt and process control.

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In the light of the problems existing in the continuous unidirectional solidification process at the present, an electric-slag induction continuous unidirectional solidification approach has been proposed. This process possesses the advantages of electro-slag remelting, induction heating, continuous casting and unidirectional solidification, and can steadily and continuously provides heating, melting, refining and heat preservation simultaneously. Therefore, it is not only favorable to obtain high-quality molten metal and relatively high temperature gradient, but it can widen the scope of the unidirectionally solidified alloys. This paper aims to study the whole solidification of the QAl9-4 Cu-Al alloy by using this new continuous unidirectional solidification equipment so as to promote the further development of the continuous unidirectional solidification technology.

2 EXPERIMENTAL

The schematic diagram of the electric-slag induction continuous unidirectional solidification equipment is show in Fig.1. It is mainly composed of electro-slag remelting system, induction heating system, cooling system, pulling system, controlling system and electrical system. The electro-slag system melts and refines the metal or alloy, preserves the heat and continuously supplies melt; the induction heating system heats the mold, makes its temperature be slightly higher than the melting point of the cast alloy so as to avoid nucleating on the mold wall, andadjusts the temperature distribution on mold wall; the heated mold and the strong heating and cooling systems creat the conditions for unidirectional solidification; the pulling system draws the

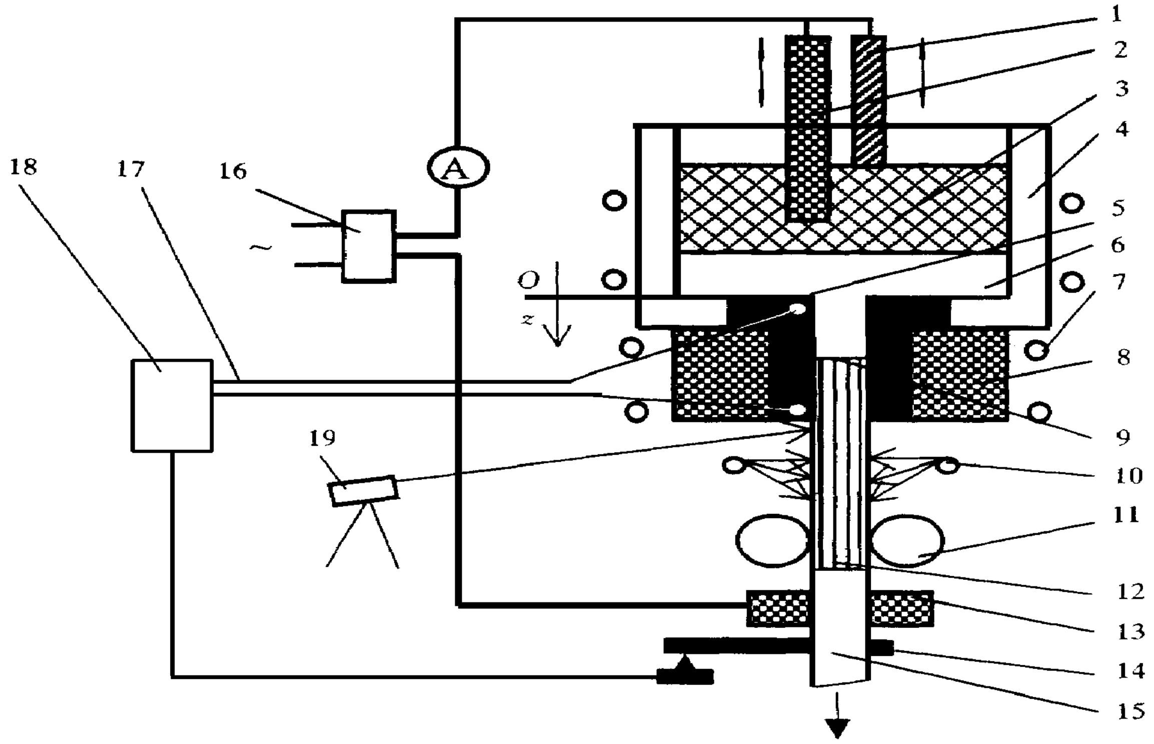

Fig.1 Schematic diagram of electro-slag induction continuous unidirectional solidification
1 —Consumable electrode; 2 —Graphite electrode; 3 —Rod slag; 4 —Crucible; 5 —Mold; 6 —Molten metal; 7 —Inductor coil; 8 —Graphite; 9 —Liquid-solid interface; 10 —Water-spraying nozzle; 11 —Pulling device; 12 —Ingot; 13 —Brush; 14 —Displacement sensor; 15 —Ingot bar; 16 —Transformer; 17 —Thermocouple; 18 —Multipoint equilibrium recorder; 19 —Infrared ray temperature-measuring instrument

ingot bar from the mold so as to realize continuous casting; the infrared ray thermosistor, the temperature-controlling thermocouple and the displacement sensor are used to control and monitor the whole process. The QAl9-4 Cu-Al alloy was unidirectionally solidfied by the equipment as shown in Fig.1. The electric-slag is CaF$_2$ and NaF in a mass ratio of 80∶20[7]. The voltage of the electric-slag furnace is 24 V.

3 RESULTS AND DISCUSSION

3.1 Control of electro-slag induction continuous unidirectional solidification process

In the continuous unidirectional solidification process, the temperature distribution along the central axis of the mold can sufficiently determine the position of the solid-liquid interface which is imperative to the steady progress of the solidification process. For this reason the thermocouple is fixed in special ingot-leading rod and located on the central axis of the mold entrance. In the solidification process, the thermocouple moves synchronically with the ingot-leading rod, thus it can measure the distribution of temperature along the height in the central axis. The results are shown in Fig.2. However, this method can not be used to control the steady progress of the solidification process, and it is necessary to find more practical controlling methods. Fig.2 also presents the temperature distribution 2 mm from the inner wall of the mold under the same conditions. It is thus clear that the temperature at this position is very similar to that of the melt in the mold. Although the height of the solid-liquid position reflected by the former is slightly lower, the difference is very small. Figs.3 and 4 present several temperature gradients in the mold wall and the solid-liquid interface positions determined by the temperature distribution of the melt along the central axis and the temperature distribution in the mold wall. It is thus evident

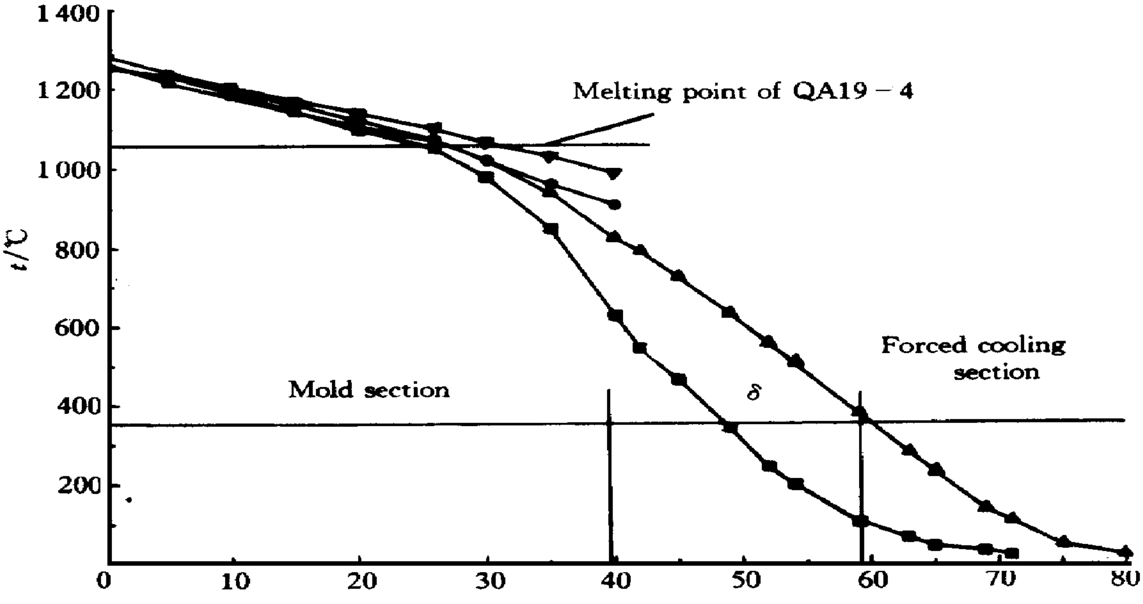

Fig.2 Temperature distributions in QAl9-4 electric-slag induction continuous unidirectional solidification process

	I/A	Q/(L·h^{-1})	δ/mm	R/(mm·s^{-1})	
■	300	1 000	20	0.09	Axis
●	300	1 000	20	0.09	Wall of mold
▲	200	800	20	0.24	Axis
▼	200	800	20	0.24	Wall of mold

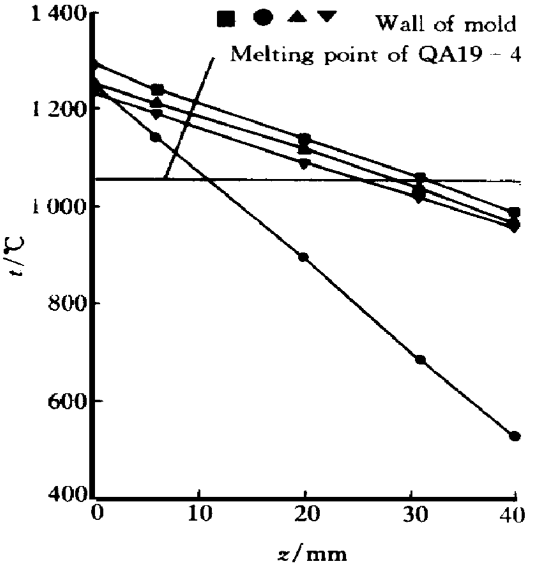

Fig.3 Temperature gradient of wall of mold

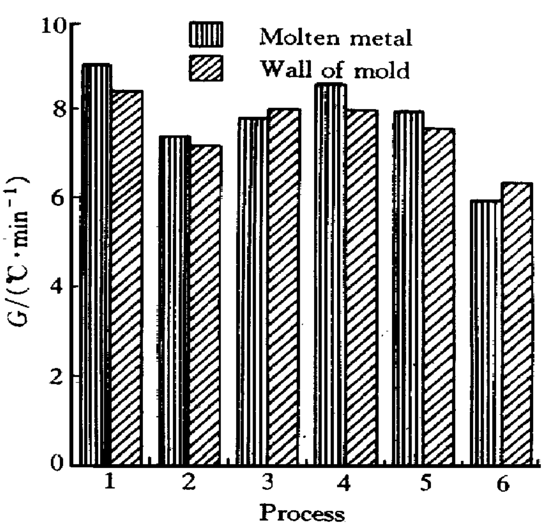

Fig.4 Temperature gradient of molten metal and wall of mold

1 — $I = 300$ A, $Q = 1\ 000$ L·h^{-1}, $R = 0.09$ mm·s^{-1};
2 — $I = 200$ A, $Q = 800$ L·h^{-1}, $R = 0.24$ mm·s^{-1};
3 — $I = 200$ A, $Q = 800$ L·h^{-1}, $R = 0.42$ mm·s^{-1};
4 — $I = 200$ A, $Q = 800$ L·h^{-1}, $R = 0.50$ mm·s^{-1};
5 — $I = 200$ A, $Q = 1\ 200$ L·h^{-1}, $R = 0.30$ mm·s^{-1};
6 — $I = 200$ A, $Q = 600$ L·h^{-1}, $R = 0.54$ mm·s^{-1}

from the above results that the approximate position of the solid-liquid interface can be conveniently determined by the temperature distribution in the mold wall, and inductly controlled by adjusting the temperature distribution in the mold wall.

3.2 Effects of technological parameters on position of solid-liquid interface

In the continuous unidirectional soliditication process, the position of the solid-liquid interface affects the stability of the solidification process and the solidification quality, and itself is affected by the other technological parameters. When the output power of the high frequency induction is definite, the effects of current I, cooling water flow rate Q, cooling distance δ (from the upper fringe of the water-spring zone to the mold outlet) and pulling rate R, which are indirectly obtained from the temperature distribution in the mold wall, are shown in Fig.5. These curves reflect the effect tendencies of the technological parameters on the solid-liquid interface. The causes of their effects can be analyzed as follows. 1) The smaller the cooling distance, the larger the cooling intensity, the heat in the metal and the mold is rapidly transferred out through the solidified solid phase, as a result the solid-liquid interface is forced to move upward. 2) The current leads to the rise of the temperature of the melt, and that of the mold through the heat transfer from the melt to it, thus lowering the solid-liquid interface. 3) The coefficient of heat transfer between the cooling water and ingot bar is proportional to 2/3 power of the cooling water flow rate Q[8], therefore when Q reaches a certain large value, the increase of cooling ability slows down with increasing Q value. 4) The change of the pulling rate does not increase or decrease the heat in the whole system, but its increase makes the high temperature molten metal flow down, and consequently increase the temperature of the mold wall, thus making the solid-liquid interface move downward. The above effect laws of the technological parameters are important to quantitatively explain the effects on the solidification process of single parameters, especially those of the alloys with small heat transfer coefficients. However, the effects of the various technological parameters on the position of the solid-liquid interface

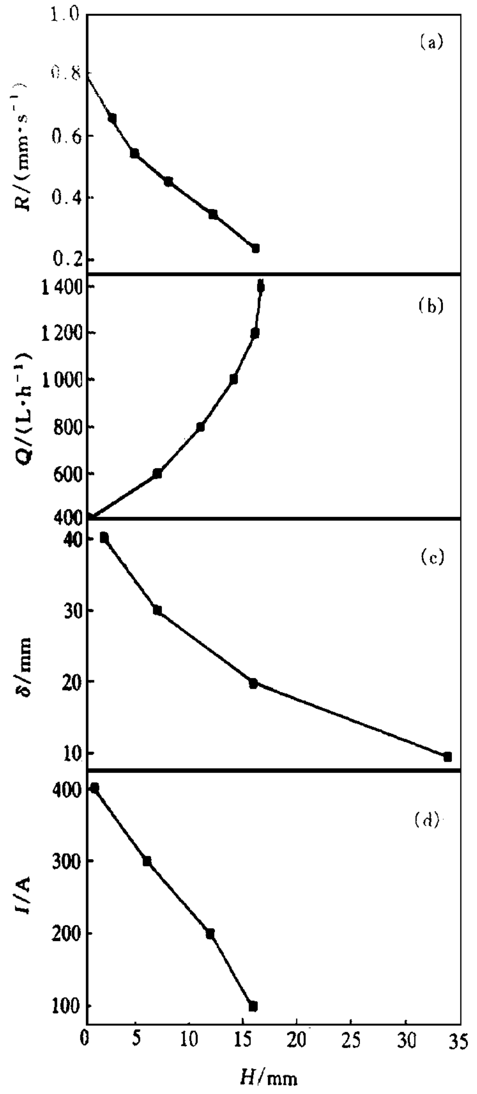

Fig.5 Effects of craft parameters on height H of liquid-solid interface
(a) — $Q = 1\,200$ L·h^{-1}, $\delta = 20$ mm, $R = 0.24$ mm·s^{-1};
(b) — $I = 100$ A, $\delta = 20$ mm, $R = 0.24$ mm·s^{-1};
(c) — $Q = 1\,200$ L·h^{-1}, $I = 100$ A, $R = 0.24$ mm·s^{-1};
(d) — $Q = 1\,200$ L·h^{-1}, $\delta = 20$ mm, $I = 100$ A

are not completely independent, there exist internal relations between them determined by the temperature distribution of the system. The general relations between the technological parameters in the unidirectional solidification process have been described by the authors in Ref.[9], theoretical analyses and calculations of the internal relations between the technological parameters in the electric-slag induction continuous unidirectional solidification process will be reported elsewhere.

The change of the height of the solid-liquid interface comprehensively reflects the effects of various technological parameters, therefore the mutual matching of them plays a key role in the electric-slag induction continuous unidirectional solidification process.

3.3 Unidirectionally solidified microstructure by electro-slag induction continuous unidirectional solidification

Fig.6 shows the low-magnification microstructure and interface shape of QAl9-4 by electric-slag induction continuous unidirectional solidification, while Fig. 7 shows the metallographs of QAl9-4 at different currents. In the growth process of the columnar grains, their growth direction is decided by the direction of heat transfer and normal to the solid-liquid interface. This relation is used by Ryuji *et al*[10] to deduce the shape of the solid-liquid interface in the solidification process. Fig.6(a) reveals that there exists a small angle between the growth direction of the columnar grains and the pulling direction and the solid-liquid interface presents a little fan-like shape. Fig.6(b) schematically describes the shape of the solid-liquid interface at this moment, and it is thus clear that the solid-liquid interface protrudes toward the molten melt. This agrees with the height difference between the positions of the solid-liquid interface at the ingot center and fringe as shown in Fig.2. It is very important to control the solid-liquid interface to be planar or slightly protrude toward the molten melt in the continuous unidirectional solidification process so as to obtain excellent unidirectionally solidified microstructure. Fig. 7 shows that the metallographs of QAl9-4 prepared by the electric-slag induction continuous unidirectional solidification process are typical unidirectionally solidified microstructures.

Fig.8 gives a photograph of the real object of QAl9-4 ingot bars produced by the electric-slag induction continuous unidirectional process. It is thus clear that its surface quality is similar

Fig.6 Microstructures and interface shape of QAl9-4 prepared by electric-slag induction continuous unidirectional solidification
(a) —Microstructures; (b) —Liquid-solid interface shape

Fig.7 Metallographs of QAl9-4 prepared by electric-slag induction continuous unidirectional solidification
(a) —I = 100 A; (b) —I = 300 A; (c) —I = 600 A

to that of OCC approach, namely, this approach can be used to produce ingot with good surface brightness.

3.4 Revitalization of down-pulling continuous unidirectional solidification process

In the OCC approaches, the down-pulling process has most strong points, but the easy occurrence of leaking out in this process makes it almost impossible to control the solidification process, therefore it was discarded by its inventor not long after its emergence. This is due to the facts that there does not exist temperature gradient in the mold wall in the OCC approaches, and that the solid-liquid interface is located outside the mold outlet, the height of the interface is not allowed to fluctuate. While in the solidification process proposed by the authors, there is a proper temperature gradient in the mold wall and the mold presents a regular cone shape, therefore the solid-liquid interface is automatically located at where the temperature of the inner mold wall equals the melting point of the cast metal or alloy and a membrane connection is formed between the solidified solid phase and the mold wall, as shown in Fig.9. Thus the height of the solid-liquid interface is allowed to fluctuate in a large range and it is not easy to create leaking-out, meanwhile, the surface quality of the ingots can be guaranteed. When the taper of the

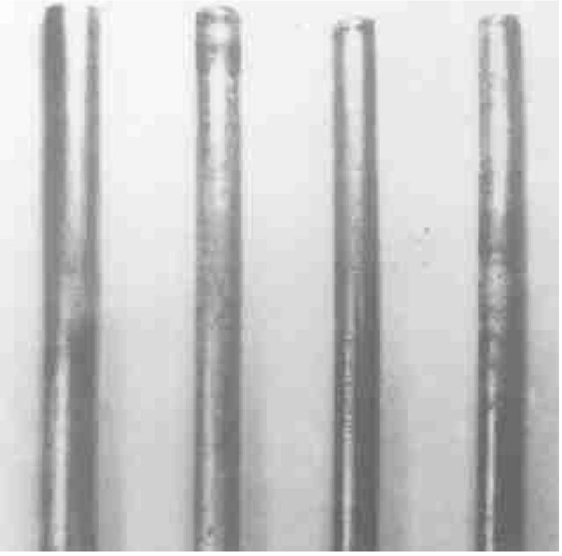

Fig.8 Bar of QAl9-4 prepared by electric-slag induction continuous unidirectional solidification

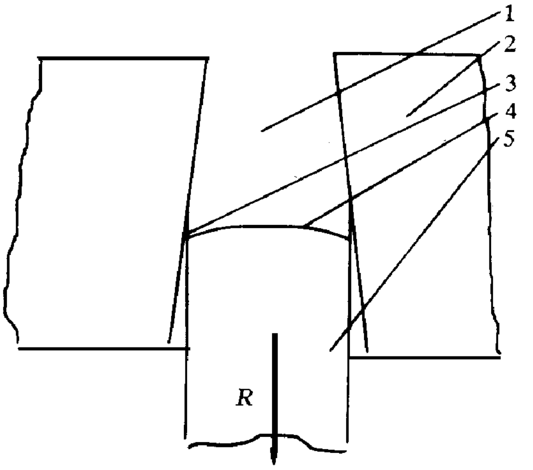

Fig.9 Schematic diagram of continuous unidirectional solidification process

1 — Molten metal; 2 — Mold; 3 — Liquid membrane; 4 — Liquid-solid interface; 5 — Ingot

mold is not properly controlled, there indeed easily occurs unstability of cross-section dimensions. This unfavourable effect can be reduced to the minimum degree by adjusting the taper of the mold. Therefore, the emergence of the electro-slag induction continuous unidirectional solidification process and promotes the continuous unidirectional solidification to be used for the solidification of various kinds of high point metals and alloys.

4 CONCLUSIONS

(1) The electro-slag induction continuous unidirectional solidification equipment can steadily realize the continuous unidirectional solidification of QAl9-4 alloy, and revitalize the down-pulling continuous unidirectional solidification process.

(2) The temperature distribution along the inner wall of the mould can approximately reflect the temperature distribution of the melt in the mold. It is feasible that the electro-slag induction continuous unidirectional solidification process be controlled by the temperature distribution along the inner wall of the mold.

(3) The mutual matching of the technological parameters is the key to stabilize the electro-slag induction continuous unidirectional solidification process.

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